Available online at www.sciencedirect.com

SCIENCE DIRECT®

PERGAMON

Acta Astronautica 57 (2005) 566–578

ACTA ASTRONAUTICA

www.elsevier.com/locate/actaastro

The Mars Reconnaissance Orbiter Mission

James E. Graf[a,*], Richard W. Zurek[a], Howard J. Eisen[a], Benhan Jai[a], M.D. Johnston[a], Ramon DePaula[b]

[a] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA*
[b] *Science Mission Directorate, NASA Headquarters, USA*

Available online 10 May 2005

Abstract

The Mars Reconnaissance Orbiter (MRO) will be launched in August 2005 by an Atlas V 401 expendable launch vehicle from Cape Canaveral Air Force Station, USA. It will deliver to Mars orbit a payload to conduct remote sensing science observations, identify and characterize sites for future landers, and provide critical telecom/navigation relay capability for follow-on missions. The mission is designed to provide global, regional survey, and targeted observations from a low 255 km by 320 km Mars orbit with a 3:00 PM local mean solar time (ascending node). During the one Martian year (687 Earth days) primary science phase, the orbiter will acquire visual and near-infrared high-resolution images of the planet's surface, monitor atmospheric weather and climate, and search the upper crust for evidence of water. After this science phase is completed, the orbiter will provide telecommunications support for spacecraft launched to Mars in the 2007 and 2009 opportunities. The primary mission ends on December 31, 2010, approximately 5.5 years after launch.

1. Introduction

The scientific objectives established by NASA's (National Aeronautics and Space Administration), Mars Exploration Program (MEP), has four major themes linked by a common strategy. The themes are

- Search for evidence of past or present life,
- Understand the climate and volatile history of Mars,
- Understand the geology and geophysics of the Martian surface and subsurface, and
- Assess the nature and inventory of resources on Mars in anticipation of human exploration.

The strategy that links these themes is the search for water. Water is key to the origin, development, and sustenance of life as we know it on Earth. It is a crucial aspect of the planet's climate and a major agent in the modification of its surface over geologic time. Water is a resource that can be exploited in the future when humans go to Mars.

In June and July 2003, NASA launched two landers called the Mars Exploration Rovers (MER) to Mars. These landers provided unprecedented in situ measurements of surface properties; however, these measurements cover relatively small geographic areas

* Corresponding author.
E-mail address: jegraf@jpl.nasa.gov (J.E. Graf).

0094-5765/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.actaastro.2005.03.043

on the Martian surface. In order to expand the critical measurement suite and extrapolate ground truth measurements from landing sites to the entire planet, the Mars Reconnaissance Orbiter (MRO) mission is planned for launch in 2005.

Imaging the surface at a ground sampling scale five times better than any prior mission, MRO will dramatically expand our understanding of Mars. The baseline science payload for the mission consists of a high-resolution imager (capable of resolving 1-m-scale objects from 300 km altitude), a visible/near infrared imaging spectrometer, an atmospheric sounder, a subsurface radar sounder, and a context optical imager. The engineering payload consists of the telecommunications package that will provide a proximity link to the surface and approach navigation support, and an optical navigation camera that will demonstrate precision entry navigation capability for future landers.

In addition to conducting detailed global and local science investigations, the payload suite will characterize sites for future landers. In this role, the observations from the payload suite perform double duty. They will both detect potentially hazardous terrain and obstacles in candidate landing sites as well as identify interesting mineral and geological formations that are attractive targets for a lander to visit.

Presently, the MRO mission is beginning its fourth year of development. A previous paper described the initial formulation phase of this mission [1,2]; this paper provides the current development status of MRO following its successful Assembly Test, and Launch Operations Review (ARR) in March 2004. This status includes a summary of mission objectives, descriptions of the orbiter design, mission design, and operations planning activities. Fig. 1 shows an artist's rendition of the MRO spacecraft.

Fig. 1. MRO spacecraft.

2. Mission objectives

The driving theme of the MEP is to understand the role of water on Mars and its implications for possible past or current biological activity. The MRO Project will pursue this "Follow-the-Water" strategy by conducting remote sensing observations that return sets of globally distributed data that will: (1) advance our understanding of the current Mars climate, the processes that have formed and modified the surface of the planet, and the extent to which water has played a role in surface processes; (2) identify sites of possible aqueous activity indicating environments that may have been or are conducive to biological activity; and (3) thus identify and characterize sites for future landed missions.

The MRO mission has the primary objective of placing a science orbiter into Mars orbit to perform remote sensing investigations that will characterize the surface, subsurface and atmosphere of the planet and will identify potential landing sites for future missions. The MRO payload will conduct observations in many parts of the electromagnetic spectrum, including ultraviolet and visible imaging, visible to near-infrared imaging spectrometry, thermal infrared atmospheric sounding, and radar subsurface profiling, at spatial resolutions substantially better than any preceding Mars orbiter. In pursuit of its science objectives, the MRO mission will

- Characterize Mars's seasonal cycles and diurnal variations of water, dust, and carbon dioxide.
- Characterize Mars's global atmospheric structure, transport and surface changes.
- Search sites for evidence of aqueous and/or hydrothermal activity.
- Observe and characterize the detailed stratigraphy, geologic structure, and composition of Mars surface features.
- Probe the near-surface Martian crust to detect subsurface structure, including layering and potential reservoirs of water and/or water ice.

- Characterize the Martian gravity field in greater detail relative to previous Mars missions to improve knowledge of the Martian crust, lithosphere, and potentially atmospheric mass variation.
- Identify and characterize numerous globally distributed landing sites with a high potential for scientific discovery by future missions.

In addition, the MRO will provide critical telecommunications relay capability for follow-on missions and will conduct, on a non-interference basis with the primary mission science, telecom and navigation demonstrations in support of future MEP activities. Specifically, the MRO mission will

- Provide navigation and data relay support services to future MEP missions.
- Demonstrate Optical Navigation techniques for high precision delivery of future landed missions.
- Perform an operational demonstration of high data rate Ka-band telecommunications and navigation services.

2.1. Science investigations and instruments

To fulfill the mission science objectives, seven scientific investigations teams have been selected by NASA. Four teams (MARCI, MCS, HiRISE, and CRISM) are led by Principal Investigators (PI). Each PI lead team is responsible for the operation of a scientific instrument and the analysis of its data. The PI lead investigations are

- Mars Color Imager (MARCI),
- Mars Climate Sounder (MCS),
- High Resolution Imaging Science Experiment (HiRISE), and
- Compact Reconnaissance Imaging Spectrometer for Mars (CRISM).

In addition to the PI lead teams, there are two investigation teams that will make use of facility instruments. The facility instruments are:

- Context Imager (CTX), and
- Shallow (Subsurface) Radar (SHARAD).

The MARCI PI and Science Team will also act as Team Leader (TL) and Team Members for the CTX facility instrument. The Italian Space Agency (ASI) will provide a second facility instrument, SHARAD, for flight on MRO. ASI and NASA have both selected members of the SHARAD investigation team with ASI appointing the Team Leader and NASA appointing the Deputy Team Leader.

In addition to the instrument investigations, Gravity Science and Atmospheric Structure Facility Investigation Teams will use data from the spacecraft telecommunications and accelerometers, respectively, to conduct scientific investigations.

High Resolution Imaging Science Experiment (*HiRISE*): HiRISE is capable of unprecedented image quality, resolution and coverage, relative to previous Mars missions. The instrument is being provided by the University of Arizona. Dr. Alfred S. McEwen is the PI. The instrument aperture is 50 cm and capable of a ground scale factor of 30 cm/pixel at 300 km altitude. The camera features a 1.15° FOV, which corresponds to a swath width of 6 km from 300 km. Images may be taken in various data modes and its image size can be between a few megabits and 28 megabits.

Compact Reconnaissance Imaging Spectrometer for Mars (*CRISM*): The CRISM will provide high-resolution hyperspectral images of areas on Mars in wavelengths from 0.4 to 4.0 μm (visible to short-wave infrared) for identifying key mineralogical indicators of water and hydrothermal systems at spatial scales smaller than a football field. Such data will be vital for targeting future landed missions. CRISM is provided by the Johns Hopkins University Applied Physics Laboratory. Dr. Scott Murchie is the PI. CRISM features a single Ritchey-Chretien telescope with two spectrometers. The telescope has a 10 cm aperture with a 2.06° field-of-view. The entire instrument is mounted on a gimbal, which allows it to follow a specific target on the surface as the orbiter flies overhead. The gimbal can scan a range of ±60° in the along-track direction.

Mars Climate Sounder (*MCS*): The MCS is a reflight of an investigation flown on Mars Climate Orbiter (MCO). The purpose of this instrument is to explore the structure and aspects of the circulation of the atmosphere. This includes mapping the thermal structure of the atmosphere from the surface to an altitude of 80 km, with a vertical resolution of 5 km and mapping the seasonal and spatial variability of atmospheric pressure. The PI is Dr. Daniel J. McCleese from JPL. MCS consists of two identical, 4 cm aperture telescopes mounted on an articulating pedestal. This instrument does not require pointing by the spacecraft. The articulation allows the instrument to view the surface of Mars, the limb of Mars, space, and calibration targets, while maintaining the orientation of the orbiter. MCS has extremely low data rates and will be operated continuously over the duration of the mission.

Mars Color Imager (*MARCI*): The MARCI is another instrument selected as part of the reflight of the MCO investigations. The PI is Dr. Michael Malin from Malin Space Science Systems (MSSS). MARCI will take low spatial resolution observations of the atmosphere, providing daily global views of Martian activity, and examine surface features characteristic of the evolution of the Martian climate over time. This instrument is nadir-pointed and has a FOV of 180°, which allows it to see limb-to-limb. MARCI has a selectable resolution between 1 and 10 km/pixel using one of its five visible bands. Resolution using one of its two UV bands provides a resolution of better than 10 km/pixel.

Context Camera (*CTX*): MSSS is providing the CTX as a facility instrument, which will provide panchromatic context imaging for the targeted investigations and which will independently address the MRO science goals. In its support role, CTX typically will be operated simultaneously with the higher-resolution instruments. The team leader for this investigation is Dr. Michael Malin from MSSS. This instrument has a 5.8° field-of-view through its 10.8 cm aperture, which is capable of a ground sample distance of 6 m/pixel from an altitude of 300 km. The 5000-pixel detector produces a swath width of 30 km.

Shallow Radar (*SHARAD*): The SHARAD will be used to search for ground ice or water and subsurface structure. SHARAD is being provided by the Italian Space Agency (ASI). This instrument is a nadir-looking radar sounder with downtrack synthetic aperture capabilities. SHARAD operates at the 15–25 MHz frequency bands, and has a vertical resolution of approximately 15 m. SHARAD is capable of probing as deep as 1 km below the surface, but typically will profile structures closer to the surface. SHARAD will be operated primarily at night over selected targets, with an occasional polar observation across the terminator to 60° latitude. SHARAD is located on the aft deck of the orbiter and its 10 m antenna will be deployed once the orbiter is in the primary science orbit.

Facility Investigations: In addition to the science instruments, there are two science investigations that rely on spacecraft subsystems to provide data. Dr. Maria T. Zuber is the TL for the Gravity Science investigation. By tracking the orbiter in the primary science phase, investigators will be able to better map the gravity field. Investigations on the structure of the atmosphere will be conducted using the data collected from the accelerometers during aerobraking. A facility investigation team led by Dr. Gerald Keating will conduct this analysis.

These MRO scientific observations will be carried out for one Mars year or more in order to characterize the full seasonal variation of the Martian climate and to target hundreds of globally distributed sites with high potential for further scientific discovery. The individual science instrument capabilities are summarized in Table 1.

2.2. Engineering payloads

To fulfill mission objectives of the MEP, MRO will carry the following engineering payloads and equipment:

- Electra, UHF communications and navigation package,
- Optical Navigation (Camera), and
- Ka Band Telecommunication Equipment.

Electra: Electra is a UHF telecommunications package that will be used to provide a command and telemetry, or proximity link as well as collecting Doppler data for navigation to the surface and support Mars approach navigation. Electra will provide near omni-directional coverage of surface assets via its UHF antenna. It will also contribute navigational-related data in the form of one-way Doppler measurements through its Ultra Stable Oscillator (USO) and two-way Doppler measurements through the use of a transponder on other spacecraft or landed asset. It can also provide one- and two-way ranging measurements.

Optical Navigation Camera: The Optical Navigation camera carried on board the MRO is part of a tech-

Table 1
Science investigation objectives

Instrument	Type	Measurement objectives	Science goals	Attributes
CRISM	High-Resolution Imaging Spectrometer	Hyper-spectral Image Cubes, 514 spectral bands, 0.4–4 μm, 7 nm res. From 300 km 20 m/pixel, 11 km swath.	Regional and local surface composition and morphology	Key: Moderately high spectral and spatial resolution, targeted and regional survey, very high data rate.
CTX	Mono-chromatic Context Camera	Panchromatic (minus blue) Images. From 300 km altitude: 30 km swath and 6 m/pixel. Context Imaging for HiRISE/CRISM & MRO Science	Regional stratigraphy and morphology	Key: Moderately high resolution with coverage, targeted and regional survey, high data rate.
HiRISE	High-Resolution Camera (0.5 m aperture)	Color Images, Stereo by Site Revisit From 300 km: <1 m/pixel (Ground sampling at 0.3 m/pixel) Swath: 6 km in red (broadband) 1.2 km in blue–green and NIR.	Stratigraphy, geologic processes and morphology	Key: Very high resolution, targeted imaging, very high data rate.
MARCI	Wide-Angle Color Imager	Coverage of atmospheric clouds, hazes and ozone and surface albedo in 7 color bands (0.28–0.8 μm) (2 UV, 5 visible).	Global weather and surface change	Key: Daily global coverage, daily global mapping, continuous ops dayside, moderate data rate.
MCS	Atmospheric Sounder	Atmospheric profiles of water, dust, CO_2 and temperature, polar radiation balance, 0–80 km vertical coverage, vertical resolution ~ 5 km.	Atmospheric structure, transport and polar processes	Key: Global limb sounding, daily, global-limb and on-planet mapping; cont. ops. day/night, low-data rate.
SHARAD	Shallow Subsurface RADAR	Ground penetrating RADAR. Transmit split band at 20 MHz <1 km; 10–20 m vert. resolution, 1 km $\times$ 5 km	Regional near-surface ground structure	Key: Shallow sounding regional profiling, high data rate.

CRISM: PI, Scott Murchie, Johns Hopkins University Applied Physics Lab (JHUAPL); CTX: TL, Michael Malin, Malin Space Science Systems (MSSS); HiRISE: PI, Alfred McEwen, University of Arizona; MARCI: PI, Michael Malin, Malin Space Science Systems (MSSS); MCS: PI, Daniel J. McCleese, Jet Propulsion Lab (JPL); SHARAD: TL, Roberto, Seu, University of Rome, Italy; DTL Roger Phillips, Washington University.

nology demonstration experiment. The camera will acquire images of Mars and its moons, Phobos and Deimos. On future missions, it could yield more precise entry for Mars landers. The camera is located on the aft deck of the orbiter and will be pointed in the direction of Mars during approach. This allows the orbiter to acquire the appropriate Optical Navigation frames, while minimizing the amount of slewing required by the orbiter. This camera has an aperture of 6 cm, and a 1.4° square field-of-view. The spacecraft will command shutter times and exposure durations via sequences that are generated on the ground.

Ka Band Telecommunications Demonstration: The Ka-band equipment carried onboard MRO will permit an operational demonstration of high rate science data return from a low altitude orbit at Mars. The Ka-band will be used in the same operational downlink modes as the primary X-band link, permitting a direct comparison of the two systems.

3. Orbiter description

The MRO spacecraft is, without question the state-of-the-art for planetary orbiters at Mars. The key attributes of the orbiter are as follows.

3.1. System description

The total MRO injected mass on the Atlas V 401 is 2180 kg. Of this 2180 kg, the allowable dry mass is 1031 kg; the rest of the injected mass is for needed fuel. The total dry mass supports a payload capability of 139 kg. The orbiter mass margin expected at launch is 8%. The propulsion system can deliver a total DV capability of at least 1545 m/s. The majority of that DV capability is for use to capture at Mars. To accomplish the needed targeted observations, the spacecraft is three-axis stabilized with large momentum wheels providing stability and control.

Applying lessons learned from previous missions, solar array and high-gain antenna (HGA) deployments occur shortly after launch avoiding long term deep space exposure. The antennas are arranged such that there is a reliable communications path from every orbiter attitude. To ensure safe capture at Mars, the propulsion system is fault tolerant to a single main engine out and a short duration computer reset event. To avoid the hazards and risks of a bipropellant propulsion system, MRO utilizes a monopropellant hydrazine design. Designed to aerobrake, the spacecraft will quickly "right itself" (i.e. shuttlecock) in the event of a large attitude excursion when it enters the Martian atmosphere. The use of aerobraking reduces the total DV requirements of the mission by 1200 m/s. Fig. 2 shows the spacecraft in comparison to other recent US Mars missions.

3.2. Spacecraft bus

Telecom: The telecommunications subsystem will be used for receiving commands and radiometric data and for transmitting radiometric data, science data, and engineering data back to the Earth. The telecom system consists of antennas, Traveling Wave Tube Amplifiers (TWTA), and a transponder.

The antenna system on the orbiter consists of a 3-m HGA and two low-gain antennas (LGA). The HGA will be deployed shortly after launch, and will remain deployed for the remainder of the mission. There are two LGAs mounted on the orbiter. There are three TWTAs—two for the X-band radio frequency and the other for Ka-band. The X-band TWTA is capable of radiating RF signals at a power of 100 W and the Ka-band TWTA is capable of radiating at 35 W. There are two modulation schemes to be employed by the SDST for telemetry downlink, QPSK and BPSK. The SDST will also produce delta-DOR tones, to be used for navigation at both X-band and Ka-band.

Propulsion: The propulsion subsystem will be used to perform major propulsive maneuvers such as trajectory correction maneuvers (TCM) and Mars orbit insertion (MOI). This propulsion subsystem operates in a blow-down mode for all mission phases with the exception of MOI where it is pressure regulated to provide higher thrust and lower finite burn losses. The propulsion system includes the propellant tank, pressurant tank, lines, valves, regulators, and the system of thrusters. The propulsion subsystem uses monopropellant hydrazine as fuel. The propellant tank is sized to accommodate 1220 kg of propellant.

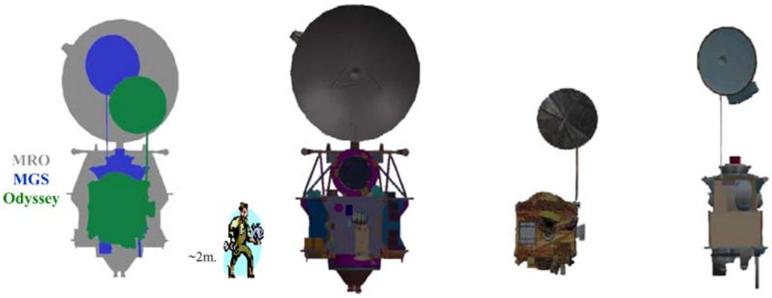
To provide translational control of the spacecraft, there are 12 thrusters: six MR-107N thrusters and six MR-106E thrusters. The MR-107N main engines, each producing 170 N of thrust, will be used to perform the MOI burn. By using six relatively small thrusters, rather than a single large main engine, the spacecraft is less susceptible to mission loss due to an engine-out failure. The MR-106E thrusters, each producing 22 N of thrust, will be used to perform the smaller TCMs, and to provide thrust vector control during the MOI burn.

Command and Data Handling (*C&DH*): The C&DH subsystem will be used to manage all forms of data on the spacecraft, including both commands and telemetry. The key features of the C&DH are the Solid State Recorder (SSR) and the Space Flight Computer.

The SSR is the primary location to store instrument data onboard the spacecraft. There are two partitions in the SSR—one for raw data storage and one for processed data storage. Once the data are in the raw data storage partition in the SSR, it will be edited and formatted by the flight computer. The formatted (packetized and framed) data will be placed back on the SSR in preparation to be downlinked to the Earth. The SSR can accommodate a total of 100 Gbits of science data, for the two partitions.

The Space Flight Computer will be a RAD 750. This processor provides up to 46 MIPS (million instructions per second) of processing power for use by the science and engineering instruments as well the orbiter bus. There is also 2 Gbits of DRAM available to the Space Flight Computer that will be used to store engineering status and health telemetry.

Guidance Navigation and Control (*GNC*): The GNC subsystem is used to control the orientation of the orbiter. This subsystem relies on star trackers, sun sensors, and an Inertial Measurement Unit (IMU) to determine its attitude, and use reaction wheels and



Item	MRO	Odyssey	MGS
Launch Year	2005	2001	1996
S/C Wet Mass (kg)	2180	733	1055
Science Orbit (km)	255X320	400	400
Ground Sampling (m)	0.3	18	1.5
Data volume (Gb/sol)	20-90 *	1	0.7

Fig. 2. Comparison between MRO and other recent US spacecraft to Mars.

the reaction control system thrusters to change the orientation of the orbiter, to allow for targeting of specific sites on the surface. Sun sensors are located on the solar arrays and orbiter bus, and allow the orbiter to locate the sun in the case of a safing event. Star trackers provide the orbiter with inertial attitude data. The IMU measures accelerations and angular rates, and is used to control attitude rates as well providing short-term attitude estimates in the absence of sun sensor or star tracker data. The reaction wheel assembly (RWA) consists of three wheels mounted perpendicularly to one another, with a fourth wheel mounted in a skewed direction.

Electrical Power: The Electrical Power distribution subsystem is responsible for generating, storing, and distributing power to the orbiter systems. This system includes two solar panels and two nickel–hydrogen batteries. The solar panels are mounted on opposite sides of the orbiter capable of two-axis articulation. This allows the orbiter to continuously track the sun. Each panel has an area of approximately 10 m^2 (20 m^2 total). The power output of the solar panels is approximately 2000 Watts at Mars at the start of the science phase. During periods of eclipse or when the orbiter turns away from the sun, energy will be provided by two nickel–hydrogen batteries. Each battery has a capacity of 50 Ah. The power margin in the primary science phase is estimated at 23%.

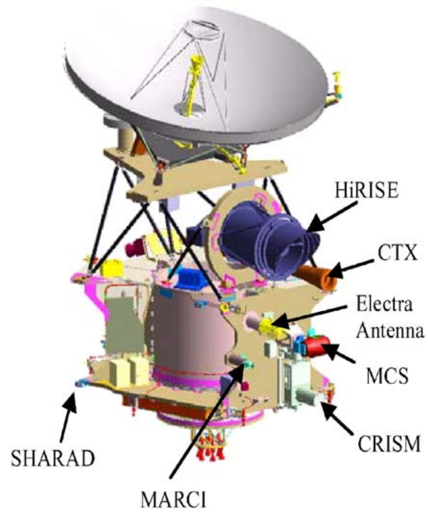


Fig. 3. Layout of instruments on nadir deck.

3.3. Payload

As discussed previously, the orbiter payload will consist of six science instruments and three engineering payloads. Fig. 3 shows the present layout of the principal science instruments.

4. Mission description

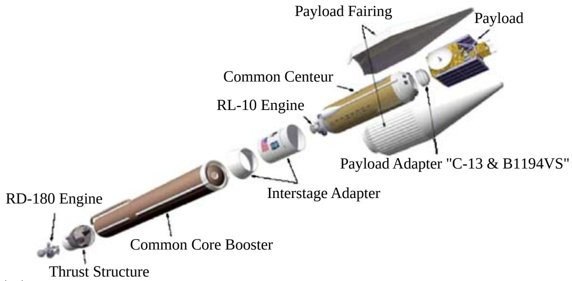
The MRO Mission has been divided into six major phases: Launch, Cruise, Approach and Orbit

Insertion, Aerobraking, Primary Science, and Relay. Each phase name characterizes the principal activity that is occurring during that time period in the mission. Designed to communicate with the Deep Space Network (DSN) via a direct X-Band link, a majority of the mission will be conducted using the 34 m antennas at two tracks per day. During MOI, supplemental coverage from the 70 m antennas will be planned. Supplemental 70 m antenna coverage is also being planned for the primary science phase. This section describes each phase of the MRO mission.

4.1. Launch

The baseline launch vehicle for the MRO mission is the Lockheed-Martin Atlas V 401. This launch vehicle was selected by NASA-KSC (Kennedy Space Flight Center) via a competitive procurement under the NASA Launch Services (NLS) contract. The Atlas V 401 is a two-stage launch vehicle. The Atlas booster, in combination with the Centaur upper stage, delivers the MRO spacecraft into a targeted parking orbit. After a short coast, a restart of the Centaur upper stage injects MRO onto its interplanetary transfer trajectory. The launch and injection of MRO will occur during the Mars opportunity of August 2005. The launch period will open on August 10th and will have a minimum 21-day duration. Fig. 4A,B shows the Atlas V 401.

(A)



(B)

Fig. 4. (A) Atlas V 401 - first launch, August 2002; (B) Atlas V 401.

4.2. Interplanetary Cruise

The interplanetary transit time will require about 7 months (212 to 197 days depending upon launch date). Primary activities during cruise include spacecraft and payload checkout and calibration. These activities, along with daily monitoring of orbiter subsystems, will be performed in order to fully characterize the performance of the spacecraft and its payload prior to arrival at Mars.

4.3. Approach and Orbit Insertion

During the last 60 days of the interplanetary transit, spacecraft and ground activities will become focused on the events necessary for a successful arrival and safe capture at Mars. Navigation techniques will include the use of delta-DOR measurements in the orbit determination. This technique will yield a precise determination of the inbound trajectory with a series of final TCMs used to control the flight path of the spacecraft up to the MOI maneuver.

Also, during the approach phase, MRO will perform the Optical Navigation experiment. This involves pointing the optical navigation camera (ONC) at the moons of Mars—Phobos and Deimos, and tracking their motion. By comparing the observed position of the moons to their predicted positions, relative to the background stars, the ground will be able to accurately determine the position of the orbiter.

Upon arrival at Mars on March 10, 2006, the spacecraft will perform its MOI maneuver using its six main engines. MOI will insert the spacecraft into an initial, highly elliptical capture orbit with a period of 35 h. The DV required to accomplish this critical maneuver is 1015 m/s and will require approximately 25 min to complete. For most of the burn, the orbiter will be visible from the DSN stations. The reference MRO capture orbit has a period of 35 h and a periapsis altitude of 300 km. The orientation of the ascending node will be 8:30 PM LMST.

4.4. Aerobraking

One week after MOI, aerobraking operations will commence. During this time period, the orbiter will use aerobraking techniques to supplement its onboard propulsive capability and reduce its orbit period to that necessary for the primary science orbit (PSO). Aerobraking will consist of four distinct phases: a walk-in phase, a main phase, a walkout phase and a transition to the PSO. During the walk-in phase, the spacecraft establishes initial contact with the atmosphere as the periapsis altitude of the orbit is slowly lowered. This phase continues until the dynamic pressures and heating rate values required for main phase, or steady state aerobraking, are established. During the main phase, large scale orbit period reduction occurs as the orbiter is guided to dynamic pressure limits. Main phase continues until the orbit lifetime of the orbiter reaches 2 days. (Orbit lifetime is defined as the time it takes the apoapsis altitude of the orbit to decay to an altitude of 300 km.) When the orbit lifetime of the orbiter reaches 2 days, the aerobraking walkout phase will begin. During the walkout phase, the periapsis altitude of the orbit will be slowly increased as the 2 day orbit lifetime of the orbiter is maintained. Once the orbit of the orbiter reaches an apoapsis altitude of 450 km, the orbiter will terminate aerobraking by propulsively raising the periapsis of its orbit out of the atmosphere.

4.5. Primary Science

The PSO has been designed to satisfy the science requirements of the mission. This orbit has the following characteristics:

- a Sun-synchronous ascending node at 3 PM local mean solar time (LMST)—daylight equatorial crossing (near polar inclination of 92.7°),
- an eccentricity and argument of periapsis that results in a low altitude "frozen" orbit (periapsis altitude of 255 km, apoapsis altitude of 320 km, and an argument of periapsis of 270°), and
- a semi-major axis that will produce a 17-day (short term) groundtrack repeat cycle (semi-major axis of 3775 km).

4.6. Relay

Following the completion of the primary science objectives of the mission, the MRO orbiter will support the MEP by providing approach navigation and relay communications support to various Mars landers and orbiters through its telecommunications/navigation subsystem. Additionally, MRO has the ability to continue its scientific observations, including evaluation of future landing sites, for an additional Mars year as an asset for the Mars Program.

4.7. Mission Timelines

To synthesize the mission design, top-level timelines have been developed for each mission phase. Fig. 5 shows the timeline of key events from launch through most of aerobraking. Launch period, mission phase durations, planned TCM events, checkout and calibration periods, the comparative navigation experiment period, MOI, Mars seasons and geometry, DSN tracking levels and Delta-DOR navigation periods are shown.

Fig. 6 shows the timeline for the Primary Science Phase. Also shown are the aerobraking termination events, the transition to the PSO, solar conjunctions, maneuver events, orbiter checkouts and calibrations, Mars seasons and geometry, DSN tracking levels, and the launch and arrival dates for the first Mars Scout Mission—the Phoenix Lander. MRO will use its high-resolution science instruments to support the Phoenix mission by performing landing site selection support. In addition, MRO will use its Electra telecom package to (a) monitor the lander's approach trajectory and its EDL (entry, descent, and landing) event, and (b) relay data to/from the Phoenix lander once it is on the surface. Phoenix surface observations are expected to last for 5 months.

5. Operations planning

To accomplish its science objectives, MRO will conduct an integrated program of three distinct observational modes:

- Daily global mapping and profiling,
- Regional survey, and
- Globally distributed targeting.

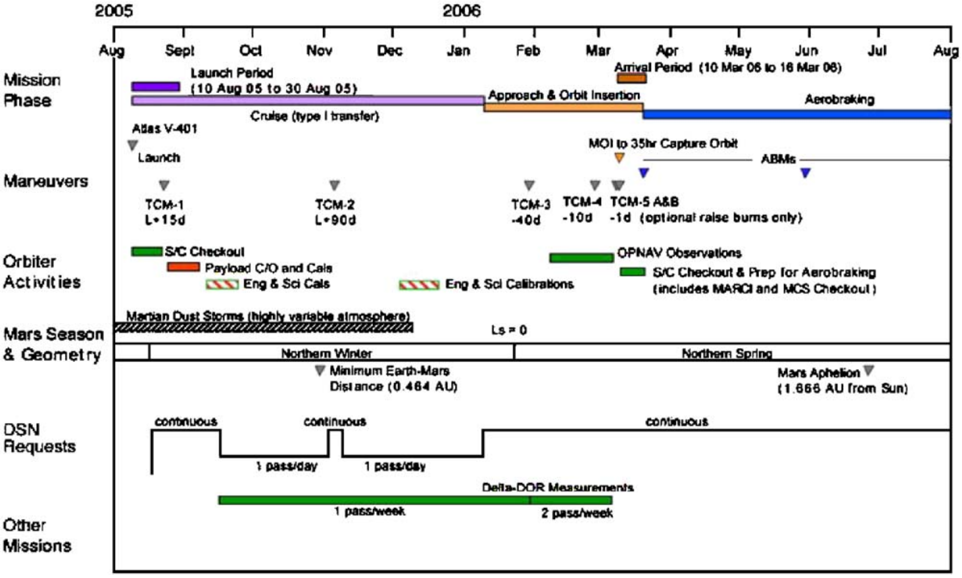


Fig. 5. MRO Mission Timeline—Launch, Cruise, Orbit Insertion, Aerobraking.

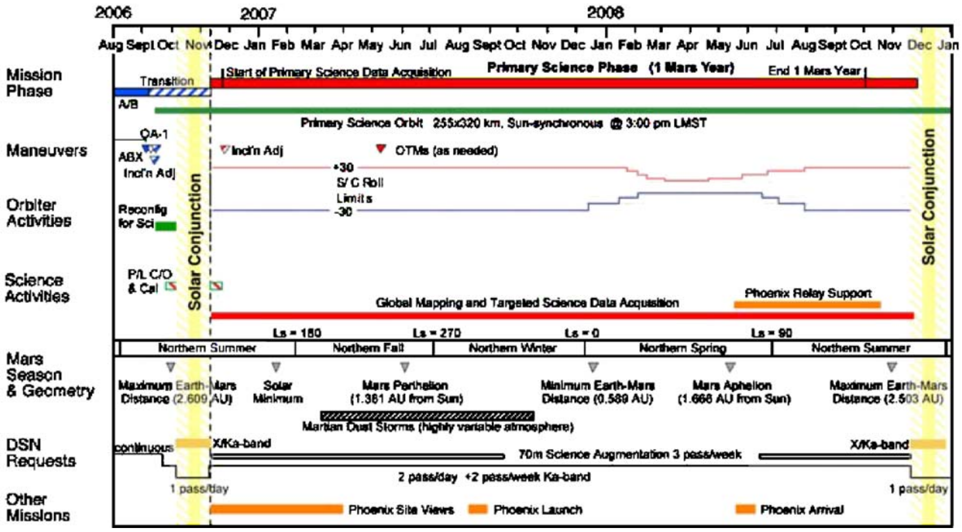


Fig. 6. MRO Mission Timeline—Primary Science.

These observation modes will be intermixed and often overlapping. Some instruments have more than one observational mode. In addition, many targeted observations will involve nearly simultaneous, coordinated observations by more than one instrument. This section describes current operations planning activities performed for MRO.

5.1. Observation modes

The science investigations are functionally divided into daily global mapping and profiling, regional survey, and globally distributed targeting investigations. The global mapping instruments are the MCS and the MARCI. The targeted investigations are HiRISE, CRISM, and CTX. The survey investigations are CRISM and CTX (in survey modes), and SHARAD. The global mapping instruments require nadir pointing, low data rate, and continuous or near-continuous operations. The global mapping investigations are expected to use less than 5% of the expected downlink data volume. The targeted and survey instruments are high data rate instruments and will require precise targeting in along-track timing and/or cross-track pointing for short periods of time over selected portions of the surface. It is expected that more than 95% of the available downlink data volume will be used for targeted and survey investigations. All instruments can take data simultaneously (including Electra).

5.2. Target planning strategies—interactive and non-interactive observations

The science data acquisition strategy is predicated on the PSO characteristics, the objectives of the selected science investigations (instrument and facility teams), and the available orbiter resources and capabilities. Investigation priorities, targeted observations and data allocations will be coordinated in advance by the science teams, culminating in meetings every four weeks of the Target Acquisition Group or TAG, which includes membership from the PSG and representatives of the MEP. The TAG confirms plans for the immediate science and sequence planning cycle. For the subsequent planning cycle, the TAG will consider changes in planning guidelines, changes in instrument data allocations, and will coordinate opportunities and guidelines for survey and targeted observations.

There are two fundamental types of science observations: Non-Interactive Observations and Interactive Observations. Non-interactive observations do not require the spacecraft or other instruments to change modes or support them. Investigation teams plan their non-interactive observations independently of other investigations. Since the spacecraft is always nadir pointed for non-interactive observations, they can be made anytime unless there are interactive observations that are in conflict.

Interactive observations are those that require the spacecraft or another instrument to change its mode. Examples of this include off-nadir targeting (spacecraft rolls), observations that require suspension of MCS or solar array motion. Interactive observations are always planned and coordinated through the science planning process and ratified by the TAG.

In order to reduce pointing errors resulting from navigation uncertainties, the orbiter will use an ephemeris driven on-board pointing algorithm. The number of off-nadir targets per day is constrained to 20 per day or two per orbit for planning purposes. The orbiter is capable of acquiring up to four targets per orbit if there is a compelling need. More than 1000 targeted observations will be made during the primary science phase.

The orbiter will be able to target as many as 20 sites per day, but a single target may yield from 2 to 20 Gbits. Therefore, the possible number of targets under consideration for investigation varies considerably over the course of the mission. Data acquisition and downlink are asynchronous. Data management and downlink priority are independent of collection strategy or order.

In addition to the baseline two 8-h tracks per day during the science phase, 70 m coverage and Ka-band coverage will be requested. Seventy-meter passes will be used to augment the baseline plan, allowing for additional data return during periods where the Earth–Mars range is near its maximum. The 70 m passes will be scheduled three times per week from November 2005 to June 2007 and from February 2008 to November 2008. Ka-band capable 34 m-BWG antennas will be requested twice per week for the entire primary science phase as part of a Ka-band telecommunications technology demonstration. Since gravity science on MRO uses two-way x-band Doppler data, any tracking shared with other missions using Multiple Spacecraft Per Aperture (MSPA) configurations will have to be carefully coordinated with DSN schedulers. The MRO spacecraft will be designed to provide at least 500 kbps at maximum range (2.67 AU) to a 34 m BWG station using Turbo 1/3 encoding.

Data volumes from MRO are calculated from the data rate at a particular time, and from the amount of time available for downlink. The time available for downlink is a function of orbit period, occultation duration, lockup time assumptions, tracking time assumptions, and the duration of orbiter activities that prevent downlink (e.g., HGA off-pointing). Data rate and downlink duration vary day to day. Fig. 7 shows the cumulative data volume over the course of the Primary Science Phase.

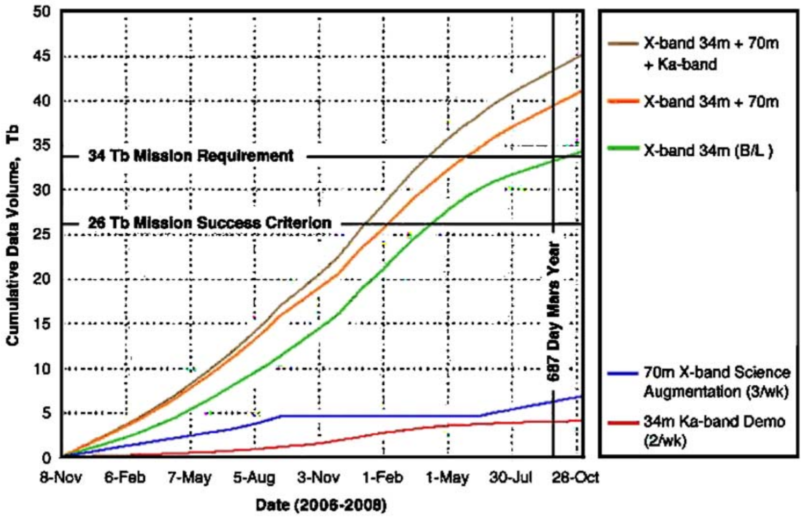


Fig. 7. Cumulative Data Volume.

6. Implementation and schedule

The MRO mission is managed by the Jet Propulsion Laboratory and its implementation relies heavily on the capabilities of industry and academia. Lockheed-Martin Astronautics in Denver, CO, was selected in October 2001 to develop the spacecraft bus, perform payload accommodations, and provide launch and operations support. In November 2001, NASA Headquarters selected the major elements of the science payload via the Announcement of Opportunity process. In May 2002, KSC selected the Lockheed-Martin Astronautics Atlas V 401 as the launch vehicle for MRO mission. The system-level Preliminary Design Review (PDR) was accomplished in July 2002 with the formal NASA confirmation of the MRO given in September 2002. The Critical Design Review was conducted in May 2003 and the ATLO Readiness Review nine months later.

As of August 2004, the engineering bus was successfully integrated and 98% of the flight software was onboard the orbiter. The Electra unit was integrated while the remaining instruments are scheduled for delivery in September 2004. The bulk of the ground system software was delivered. Mass margin at launch is approximately 8% or 80 kg while the science phase power margin is 23%.

7. Summary

MRO is a major mission of the Mars Exploration Program. This mission will greatly enhance our understanding of Mars by returning new and high resolution scientific observations. The MRO spacecraft and its scientific payload reflect a state of the art design for planetary exploration. Over the course of its mission lifetime, MRO is expected to return more than 34 Tbits of data. The analysis of this data will undoubtedly shape the future of Mars exploration for many years to come.

Acknowledgements

The authors want to thank Ms. Janis Norman, and Ms. Annie Parkhurst for their assistance in the preparation and editing of this manuscript.

The research described in this (publication or paper) was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1] J. Graf, R. Zurek, R. Jones, H. Eisen, M. Johnson, B. Jai, An overview of the Mars Reconnaissance Orbiter Mission, 2002 IEEE Aerospace Conference Proceedings, Big Sky, Montana, March 11–15, 2002.

[2] J. Graf, M. Johnston, R. Zurek, R. De Paula, H. Eisen, B. Jai, The Mars Reconnaissance Orbiter Mission, 2003 International Astronautical Federation Conference Proceedings, Bremen, Germany, September 29–October 3, 2003.